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CDF

**Search for Third Generation Leptoquarks in
p̄p Collisions at $\sqrt{s} = 1.8$ TeV**

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Search for Third Generation Leptoquarks in $\bar{p}p$ Collisions at

$$\sqrt{s} = 1.8 \text{ TeV}$$

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Abstract

We present the results of a search for third generation leptoquark (LQ) pairs in $110 \pm 8 \text{ pb}^{-1}$ of $\bar{p}p$ collisions at $\sqrt{s} = 1.8 \text{ TeV}$ recorded by the Collider Detector at Fermilab. We assume third generation leptoquarks decay to a τ lepton and a b quark with branching ratio β . We observe one candidate event, consistent with Standard Model background expectations. We place upper limits on $\sigma(\bar{p}p \rightarrow \text{LQ } \overline{\text{LQ}}) \cdot \beta^2$ as a function of the leptoquark mass M_{LQ} . We exclude at 95% confidence level scalar leptoquarks with $M_{LQ} < 99 \text{ GeV}/c^2$, gauge vector leptoquarks with $M_{LQ} < 225 \text{ GeV}/c^2$, and non-gauge vector leptoquarks with $M_{LQ} < 170 \text{ GeV}/c^2$ for $\beta = 1$.

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Many extensions of the Standard Model (S.M.) that place quarks (q) and leptons (ℓ) on an equal footing predict the existence of leptoquarks (LQ), color-triplet bosons that couple directly to $q\ell$ or $\bar{q}\ell$ pairs [1–3]. The other leptoquark quantum numbers (e.g., spin, charge, weak isospin), and the coupling strength λ to fermions, are model-dependent. The present analysis searches for leptoquarks that couple only to third generation fermions. We consider spin-0 and spin-1 leptoquarks that decay with branching ratio β to τb (charge $-\frac{4}{3}$) or $\tau \bar{b}$ (charge $-\frac{2}{3}$) [4]. For a charge- $\frac{4}{3}$ leptoquark, β is 1. A charge- $\frac{2}{3}$ leptoquark may also couple to $\nu_\tau t$ depending on the other leptoquark quantum numbers. In this case, for leptoquark mass (M_{LQ}) smaller than M_t the decay mode $LQ \rightarrow \nu_\tau t$ is kinematically forbidden, and β is equal to 1. If $M_{LQ} > M_t$ for such leptoquarks, β is less than 1, and for $M_{LQ} \gg M_t$, β approaches 0.5 [5].

We report on a search for third generation leptoquarks using $110 \pm 8 \text{ pb}^{-1}$ of $\bar{p}p$ collisions at the Tevatron Collider Detector at Fermilab (CDF). There have been no prior searches reported on third generation leptoquarks at hadron colliders. Limits from the Tevatron exclude at 95% confidence level (C.L.) first generation scalar leptoquarks with $M_{LQ} < 133 \text{ GeV}/c^2$ and second generation scalar leptoquarks with $M_{LQ} < 131 \text{ GeV}/c^2$ for $\mathcal{B}(LQ \rightarrow \ell^\pm q) = 1$ [6]. Direct searches performed at the LEP experiments exclude scalar leptoquarks of all generations with masses $\lesssim 45 \text{ GeV}/c^2$ at 95% C.L. [7]. These mass bounds are largely independent of λ [8]. In contrast, experiments at HERA [9] give limits on the leptoquark mass that depend explicitly on λ . Indirect bounds on $\frac{\lambda}{M_{LQ}}$ for scalar leptoquarks have been derived from LEP precision electroweak measurements [10]; these measurements disfavor leptoquarks that couple to the top quark. On the other hand, the properties of leptoquarks that couple only to τb pairs remain virtually unconstrained.

In $\bar{p}p$ collisions, leptoquarks can be pair-produced by gluon-gluon fusion or $q\bar{q}$ annihilation. The production cross section of leptoquark pairs depends only on the leptoquark mass, spin and the fact that the leptoquark is a color-triplet field. Because the couplings of scalar leptoquarks to gluons are model-independent and yield unique predictions for leptoquark pair production cross sections, the results presented here constrain any theory containing

spin-0 leptoquarks. In contrast, vector leptoquarks have model-dependent trilinear and quartic couplings to the gluon field. In one model, the possible gluon-leptoquark couplings are parametrized in terms of an “anomalous magnetic moment” κ [11]. This analysis considers two values of κ . One value, $\kappa = 1$, corresponds to a vector leptoquark that is a fundamental gauge boson in an extended gauge group. The other value, $\kappa = 0$, is chosen such that the production cross section is near its minimum as a function of κ , and thus provides the most conservative vector leptoquark mass limits [11].

The CDF detector has been described in detail elsewhere [12,13]. The experimental signature considered is $\tau^+\tau^-$ plus two jets in the final state in which one τ decays leptonically and the other decays hadronically. We select events satisfying a high- p_T lepton trigger [13], and containing a well-identified muon or electron candidate in the region $|\eta| < 1$ with $p_T > 20$ GeV/c [14]. Jets are found in the calorimeter using an iterative clustering algorithm that starts with a fixed cone of radius $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.4$ in η - ϕ space [15]. Hadronic τ candidates (τ -jets) are selected from jets that have uncorrected $E_T > 15$ GeV in the region $|\eta| < 1$. Jets that pass our electron criteria are excluded from consideration. In addition, the associated charged particles with $p_T > 1$ GeV/c in a 10° cone around the jet direction must satisfy the following requirements: (i) the τ -jet must have one or three charged particles; (ii) if there are three, the scalar sum p_T must exceed 20 GeV/c and the invariant mass must be smaller than 2 GeV/c²; and (iii) the leading charged particle must have $p_T > 10$ GeV/c and must not point to an uninstrumented region of the calorimeter. The charge of the τ -jet is defined as the sum of the charges of particles within 10° around the jet direction, or the charge of the particle with the highest p_T if the sum is not equal to ± 1 . The efficiency of the τ -jet criteria grows from 32% for τ -jets in the range $15 < E_T < 20$ GeV to a plateau value of 59% for $E_T > 40$ GeV [16].

Both the lepton and τ -jet are required to be isolated: for electrons and muons, the additional E_T deposited in the calorimeter within a cone of radius $\Delta R = 0.4$ around the lepton direction must not exceed 10% of the lepton E_T . Isolated τ -jets must have no charged particles with $p_T > 1$ GeV/c in the annulus between 10° and 30° around the jet axis.

Events that contain a second electron or muon are removed as possible Z bosons if $70 \text{ GeV}/c^2 < M_{\ell^+\ell^-} < 110 \text{ GeV}/c^2$. After we impose these requirements, 325 events remain in the data. In 241 events, the lepton and the τ -jet have opposite electric charges, and in 84 events the charges are the same. Monte Carlo (M.C.) studies show that the 325-event data sample is described by 32% $Z \rightarrow \tau^+ \tau^-$ and 18% $W + \text{jets}$ where $W \rightarrow e\nu(\mu\nu)$ and an associated quark or gluon jet satisfies the τ -jet requirements. The remainder of the sample contains same-sign and opposite-sign lepton plus τ -jet pairs in equal numbers, as expected from fakes from other QCD sources.

The decays of τ leptons are a significant source of neutrinos, and result in missing transverse energy in leptoquark events. To select $\tau^+ \tau^-$ events, we use the variable $\Delta\Phi$ defined as the azimuthal separation between the directions of the missing transverse energy \cancel{E}_T and the lepton. Figure 1(a) shows the $\Delta\Phi$ distribution observed in the data for events with 1- and 3-prong τ -jets. There is an excess of opposite-sign over same-sign events with $\Delta\Phi \sim 0$ where the real τ signal is expected. This excess is not present in the 2- and ≥ 4 -prong background (Fig. 1(b)). Fig. 1(c) shows the M.C. expectations for $W(\rightarrow \ell\nu) + \text{jets}$, and $Z \rightarrow \tau^+ \tau^-$. The requirement $\Delta\Phi < 50^\circ$ distinguishes $\tau^+ \tau^-$ events from backgrounds such as $W + \text{jets}$. The excess at $\Delta\Phi \sim 0$ is interpreted as $Z \rightarrow \tau^+ \tau^-$ production. In leptoquark events with $M_{LQ} = 50$ (150) GeV/c^2 the requirement $\Delta\Phi < 50^\circ$ is expected to be 43% (57%) efficient (Fig. 1(d)). In the sample of events satisfying the $\Delta\Phi$ cut, 62 events contain opposite-sign lepton plus τ -jet pairs ($\tau^+ \tau^-$ candidates), and 7 events contain same-sign pairs.

The backgrounds to leptoquark pair production can be divided into real $\tau^+ \tau^-$ backgrounds and fake events (those in which a quark or gluon fragments to form a τ -jet). We use the ISAJET Monte Carlo program [17] and a detector simulation to calculate the expected number of events from S.M. $\tau^+ \tau^-$ processes: $Z \rightarrow \tau^+ \tau^- + \text{jets}$, $t\bar{t}$, and diboson production. We estimate total fake backgrounds by the number of same-sign lepton plus τ -jet events, \mathcal{N}_{SS} . The S.M. prediction for the number of opposite-sign lepton plus τ -jet events, \mathcal{N}_{OS} , is given by the sum of \mathcal{N}_{SS} and the expected contribution from all $\tau^+ \tau^-$ sources from M.C.,

\mathcal{N}_{MC} . Symbolically, $\mathcal{N}_{\text{OS}} = \mathcal{N}_{\text{SS}} + \mathcal{N}_{\text{MC}}$. Using this formula, the S.M. prediction for the number passing the $\Delta\Phi$ requirement is 63 ± 7 opposite-sign events.

Figure 2 shows the τ -jet charged particle multiplicity in the events surviving the $\Delta\Phi$ cut. Also shown is the estimate from $Z \rightarrow \tau^+ \tau^-$ (using ISAJET), plus fakes (using the same-sign data). Figure 3 shows the inclusive jet multiplicity in $\tau^+ \tau^-$ candidate events. The agreement with the S.M. background prediction is excellent. To reduce the background from S.M. processes, we require at least 2 jets with $E_T > 10$ GeV and $|\eta| < 4.2$ in addition to the lepton plus τ -jet requirement. This cuts the $Z \rightarrow \tau^+ \tau^-$ background by a factor of 20 while retaining 40%(90%) of the signal for $M_{LQ} = 50(150)$ GeV/c². One opposite-sign event survives, but no same-sign event survives. The expected background is $2.4^{+1.2}_{-0.6}$ events, dominated by $Z \rightarrow \tau^+ \tau^- + \text{jets}$ production (2.1 ± 0.6) with the remainder from diboson and $t\bar{t}$ production.

The efficiency for detecting scalar leptoquark pairs is estimated using the ISAJET Monte Carlo program [17] and a simulation of the CDF detector. Table I shows the overall detection efficiency, ε_{LQ} , and its total fractional systematic uncertainty, δ_{tot} , as a function of leptoquark mass. The systematic error δ_{tot} includes uncertainties in the modeling of gluon radiation, in the calorimeter energy scale, in the dependence on renormalization scales, and in the luminosity measurement. The vector leptoquark pair detection efficiencies are determined using leading-order matrix element calculations for pair production [11] embedded in the PYTHIA Monte Carlo program [18] to model the full $\bar{p}p$ event structure. They differ from that of scalar leptoquark pairs by a factor 2.3(3.1) for $M_{LQ} = 50$ GeV/c² and $\kappa = 0(1)$. For larger values of M_{LQ} the difference is at the 10% level [16].

We place limits on LQ pair production, taking into account the estimated background and systematic uncertainties [19]. The 95% C.L. upper limits on the leptoquark pair production cross section times branching ratio squared are listed in Table I. Using the theoretical expectations for $\sigma(\bar{p}p \rightarrow \text{LQ } \overline{\text{LQ}}) \cdot \beta^2$, we place bounds on the leptoquark mass. Figure 4 shows the experimental bounds on $\sigma \cdot \beta^2$ compared to the leading order cross section calculations using the CTEQ-2L structure functions [20]. The data exclude scalar leptoquarks with

$M_{LQ} < 99$ GeV/c² and non-gauge vector leptoquarks ($\kappa = 0$) with $M_{LQ} < 170$ GeV/c² at 95% C.L.. Since $M_{LQ} < M_t$ in the excluded regions, the decay channel LQ → $\nu_\tau t$ is kinematically forbidden there, and is therefore not considered. For gauge vector leptoquarks the data exclude $M_{LQ} < 225$ GeV/c² for those that do not couple to $\nu_\tau t$, and $M_{LQ} < 217$ GeV/c² for those that also couple to $\nu_\tau t$.

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FIGURES

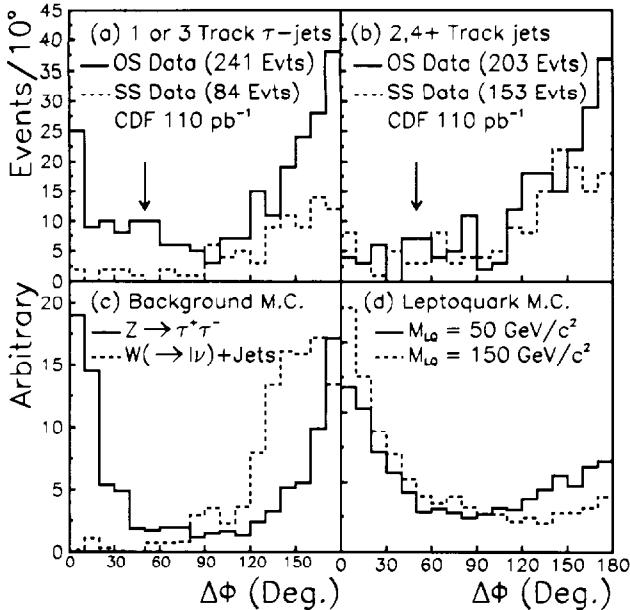


FIG. 1. Distribution of $\Delta\Phi$ between the lepton and E_T directions in the opposite-sign (solid) and same-sign (dashed) lepton plus τ -jet data (a) for τ -jets with 1 or 3 tracks and (b) for jets with 2 or ≥ 4 tracks. The arrows show the position of the cut $\Delta\Phi < 50^\circ$. The same distributions are shown for (c) $W + \text{jets}$, $W \rightarrow \ell\nu$ (dashed) and $Z \rightarrow \tau^+\tau^-$ M.C. (solid) and (d) $50 \text{ GeV}/c^2$ (solid) and $150 \text{ GeV}/c^2$ (dashed) LQ M.C. events.

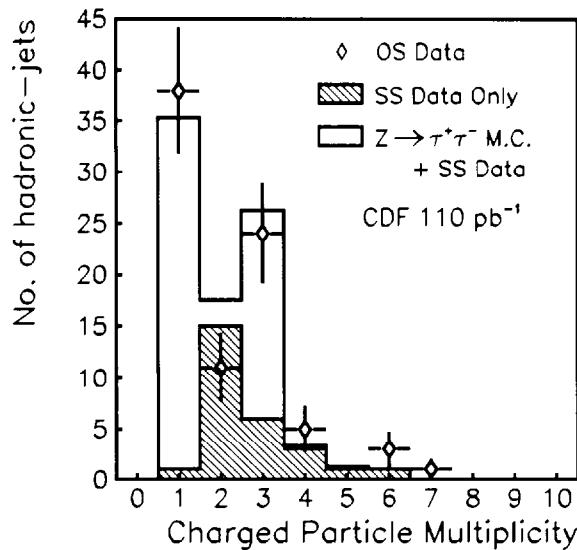


FIG. 2. Charged particle multiplicity distribution in hadronic jets after requiring $\Delta\Phi < 50^\circ$ for opposite-sign (OS) data compared to $Z \rightarrow \tau^+\tau^-$ M.C. plus the fake estimate from the same-sign (SS) data.

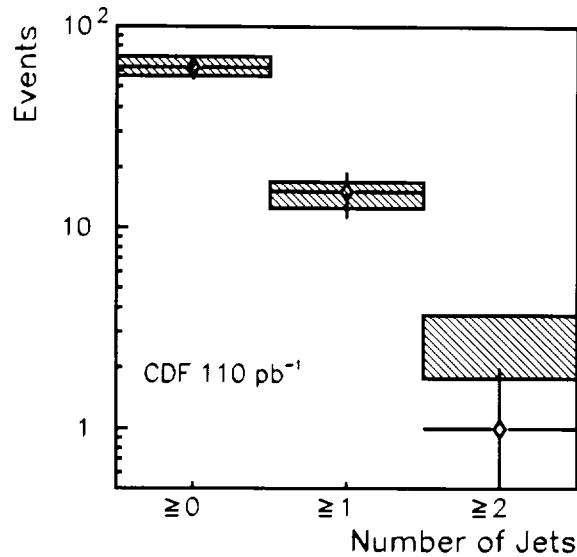


FIG. 3. The inclusive jet multiplicity distribution in $\tau^+\tau^-$ candidate events (diamonds) compared to S.M. M.C. plus the fake estimate from the same-sign data (hatched).

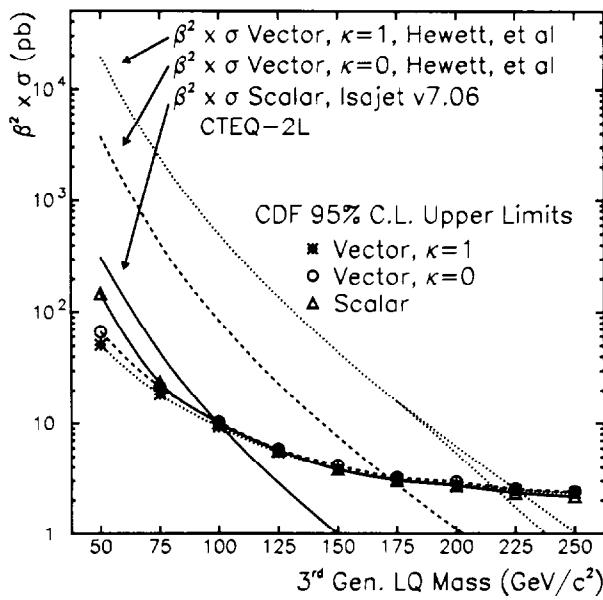


FIG. 4. The 95% C.L. upper limits on $\sigma \cdot \beta^2$ (symbols) where $\beta = \mathcal{B}(\text{LQ} \rightarrow \tau b)$ compared to the theoretical expectations. For the scalar (solid) and vector $\kappa = 0$ (dashed) leptoquark cases, β is 1. For vector leptoquarks with $\kappa = 1$ (dotted), the upper curve is for $\beta = 1$. The lower dotted curve is obtained when the decay mode $\text{LQ} \rightarrow \nu_\tau t$ is open.

TABLES

TABLE I. Summary of leptoquark detection efficiencies and fractional uncertainties, 95% C.L. upper limits on cross section times branching ratio squared (limit), and leading-order cross sections (LO) using CTEQ-2L structure functions.

M_{LQ} (GeV/c ²)	Scalar			Vector $\kappa = 0$		Vector $\kappa = 1$	
	ϵ_{LQ} (%)	δ_{tot} (%)	$\beta^2\sigma$ (pb)	limit	LO	limit	LO
50	0.029	27	150	320	67	3700	51
75	0.16	16	24	44	22	420	18
100	0.38	18	10	9.8	10	84	9.3
125	0.66	15	5.7	2.9	5.9	23	5.5
150	0.96	11	3.8	1.0	4.2	7.6	3.9
175	1.2	11	3.1	0.39	3.2	2.8	3.1
200	1.3	10	2.7	0.16	3.0	1.1	2.8
225	1.6	11	2.3	0.070	2.5	0.47	2.5
250	1.7	10	2.2	0.031	2.4	0.20	2.4
							1.0